

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188		
<p>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.</p>					
1. REPORT DATE (DD-MM-YYYY) July 2014		2. REPORT TYPE Briefing Charts		3. DATES COVERED (From - To) July 2014- August 2014	
4. TITLE AND SUBTITLE Effect of Swirl on an Unstable Single-Element Gas-gas Rocket Engine			5a. CONTRACT NUMBER In-House		
			5b. GRANT NUMBER		
			5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Matt Harvazinski, Venke Sankaran, Doug Talley			5d. PROJECT NUMBER		
			5e. TASK NUMBER		
			5f. WORK UNIT NUMBER Q0A1		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/RQRC 10 E. Saturn Blvd. Edwards AFB CA 93524-7680			8. PERFORMING ORGANIZATION REPORT NO.		
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/RQR 5 Pollux Drive. Edwards AFB CA 93524-7048			10. SPONSOR/MONITOR'S ACRONYM(S)		
			11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-RQ-ED-VG-2014-231		
12. DISTRIBUTION / AVAILABILITY STATEMENT Distribution A: Approved for Public Release; Distribution Unlimited.					
13. SUPPLEMENTARY NOTES Briefing Charts presented at AIAA JPC Conference, Cleveland, OH, 29 July 2014. PA#14400					
14. ABSTRACT In this study a series of three-dimensional unsteady reacting flow simulations are used to investigate the effect of swirl on the instability amplitude of a single-element gas-gas rocket combustor. The baseline combustor of interest is unstable because of a fuel cut-off event caused by the high-pressure waves in the combustor. Previous two-dimensional simulations have shown that swirl reduces the amplitude of the pressure oscillations compared with that of the baseline configuration. The current three-dimensional simulations show that swirl is indeed able reduce the amplitude of the instabilities, albeit not to the same extent observed in the two-dimensional simulations. We further observe that the enhanced mixing due to the swirling flow leads to a reduction in the recovery time associated with the fuel cut-off event, thereby allowing the combustor to experience a more continuous heat release. Nevertheless, unlike the two-dimensional case, the three-dimensional simulations show that the flame does not stay anchored to the dump-plane, which explains the higher relative amplitudes in this case.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Doug Talley
Unclassified	Unclassified	Unclassified	SAR	31	19b. TELEPHONE NO (include area code) 661-275-6174



Effect of Swirl on an Unstable Single-Element Gas-Gas Rocket Engine



Matthew E. Harvazinski,
Venkateswaran Sankaran,
and Douglas G. Talley

DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.



Outline



- Introduction
- Overview of the instability mechanism present in the current configuration
- Prior results form a 2D parametric study
- Results from the series of 3D simulations
- Summary



History



Combustion instability is an organized oscillatory motion in a combustion chamber sustained by combustion.

CI caused a four year delay in the development of the F-1 engine used in the Apollo program

- > 2000 full scale tests
- > \$400 million for propellants alone (2010 prices)

Irreparable damage can occur in less than 1 second.



Damaged engine injector faceplate caused by combustion instability

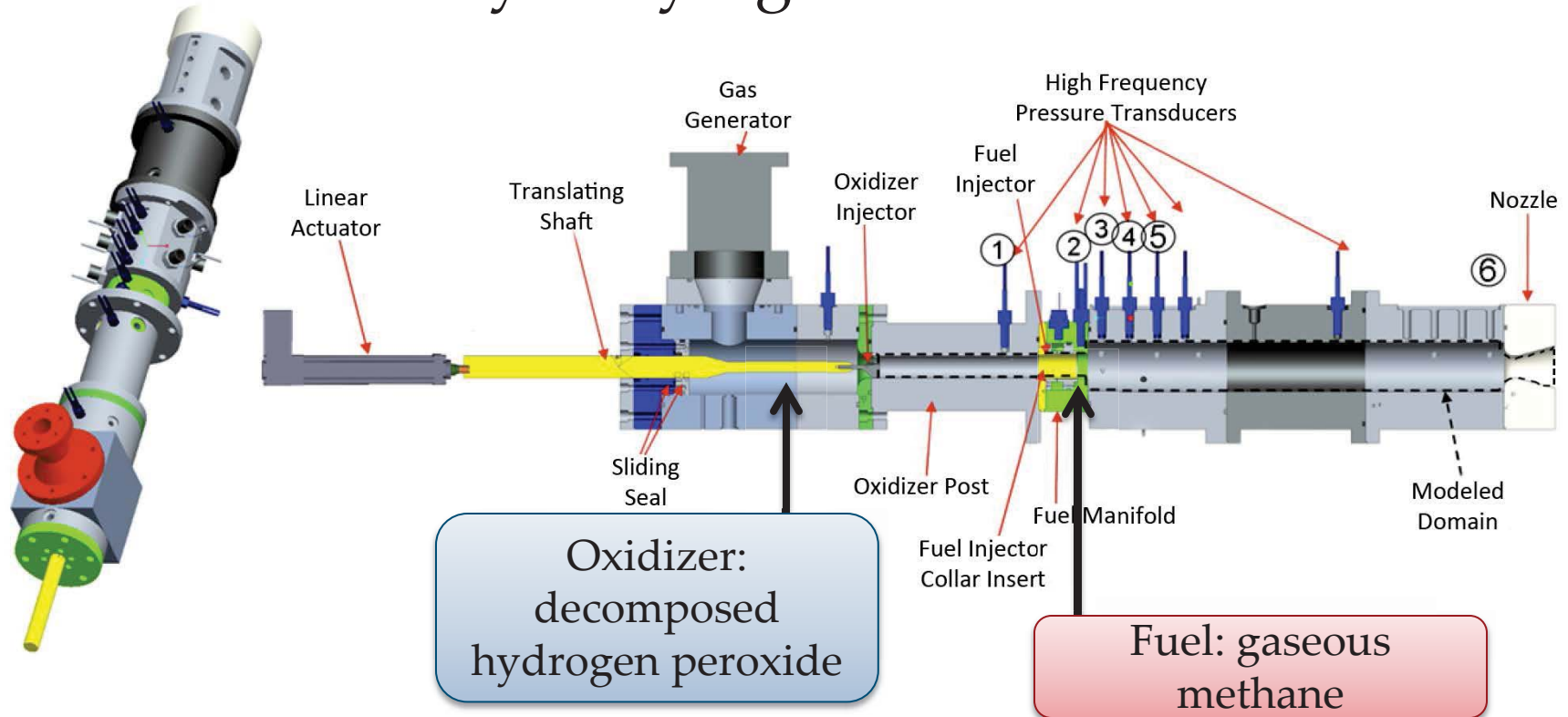
“Combustion instabilities have been observed in almost every engine development effort, including even the most recent development programs”

– JANNAF Stability Panel Draft (2010)



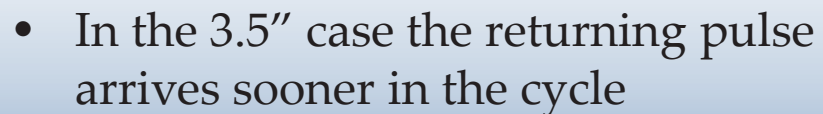
Longitudinal Experiment

Continuously Varying Resonance Chamber



Mean pressure, 1.37 MPa (200 psi)

Approved for public release; distribution unlimited



- In the 7.5" case the returning pulse arrives later in the cycle

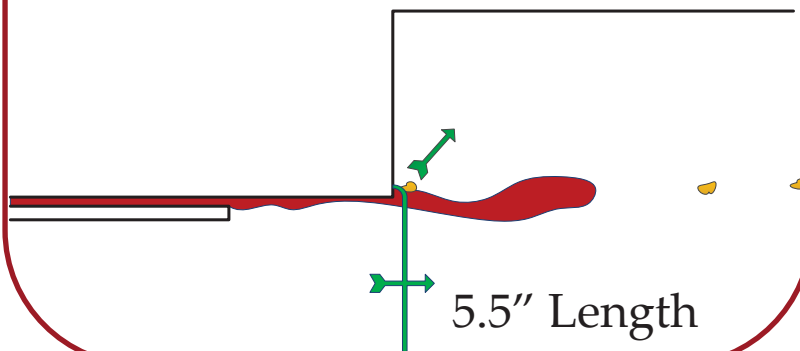


Pulse Timing II

After the fuel cutoff event the combustion restarts through one of two identified mechanisms

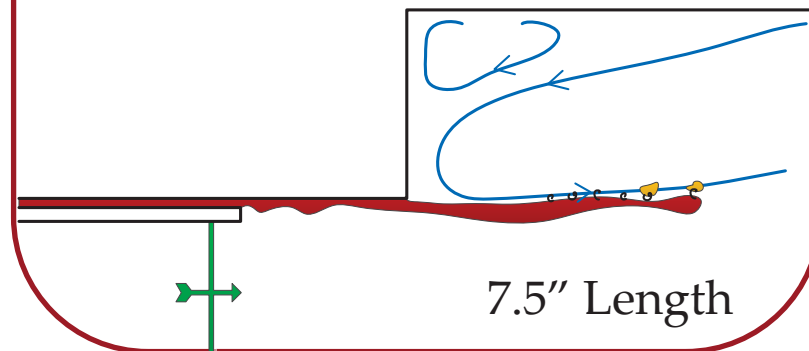
Post-coupled Ignition

Mechanism: The returning wave in the oxidizer post pushes unburnt fuel into the warm recirculating gases at the backstep where ignition takes place



Vortex Transport Mechanism:

The post wave arrives later in the cycle, the unburnt fuel slowly mixes with the recirculating gases in the shear layer. Ignition takes place in the shear layer downstream of the backstep





Baroclinic Torque

$$\frac{d\omega}{dt} = (\omega \cdot \nabla) u - \omega (\nabla \cdot u) + \frac{1}{\rho^2} (\nabla \rho \times \nabla p) + \nabla \times \left(\frac{1}{\rho} \nabla \cdot \tau \right)$$

Generation of vorticity due to misaligned density and pressure gradients

In the CVRC pressure pulses in the oxidizer post interact with the shear layer and generate vorticity



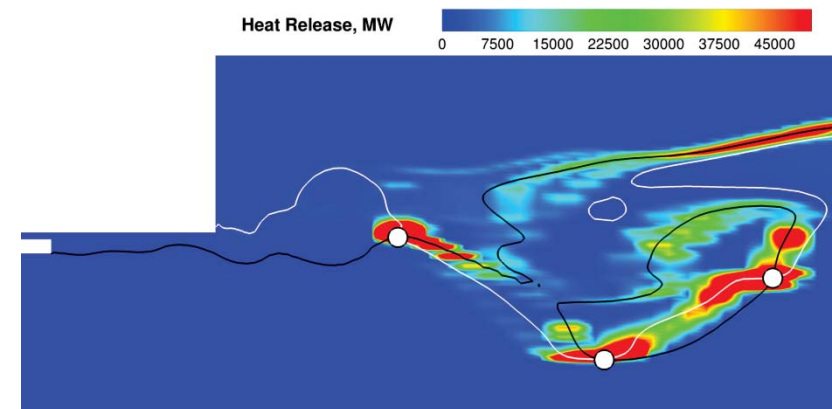
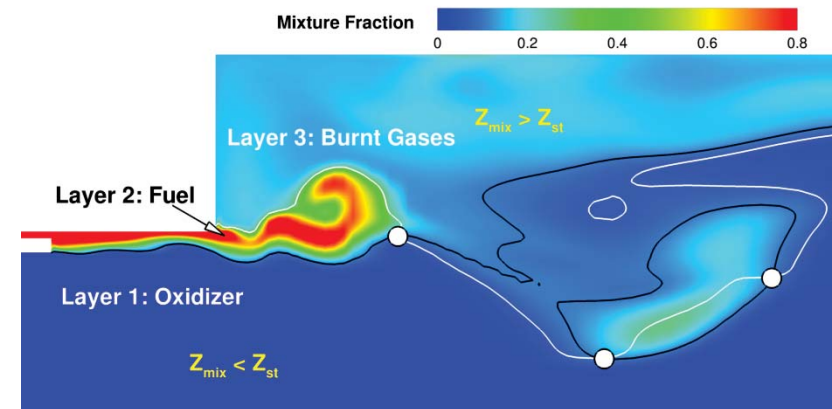
Increased vorticity results in increased mixing and generates partially premixed regions susceptible to combustion



Tibrachial Flame



- Intersection of:
 - Diffusion flame
 - Partially premixed fuel rich flame
 - Partially premixed fuel lean flame
- Location of intense heat release
- Observed in the CVRC by Garby et. al. and Guézennec et. al



White line, $T = 2000$ K

Black line, $Z = Z_{st} = 0.095739$

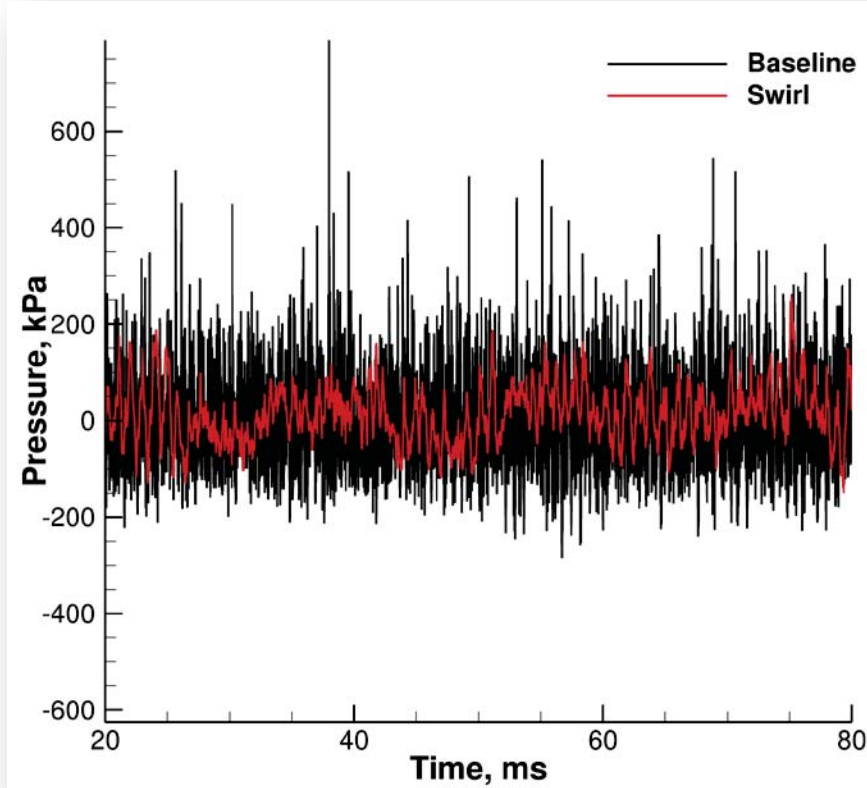
$$Z = \frac{\nu_{st} Y_{CH_4} - Y_{O_2} + Y_{O_2}^0}{\nu_{st} Y_{CH_4}^0 + Y_{O_2}^0}$$



2D Parametric Study



2D Swirl shows substantial reductions in amplitude



Case	p'_{ptp} , kPa	Frequency, Hz
Experiment	387.15	1324
BL	135.19	1460
S-1	78.82	1480
S-2	65.00	1480
S-3	40.72	1480
S-4	60.61	1480

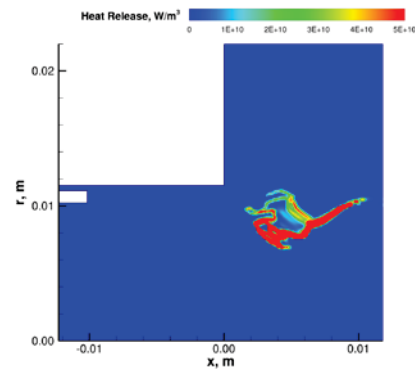
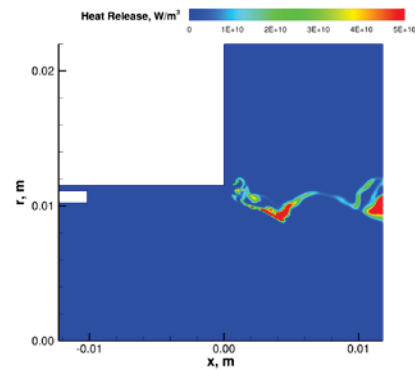
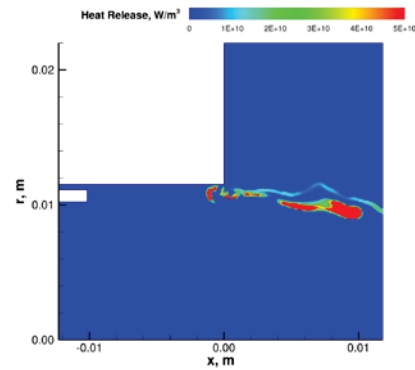
Concerns:

- Total amplitudes in 2D are lower compared with 3D
- Swirl component is assumed axisymmetric and may be stronger than 3D

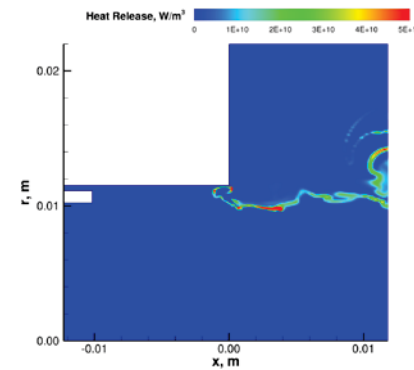
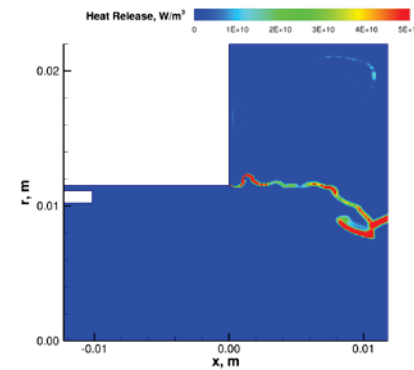
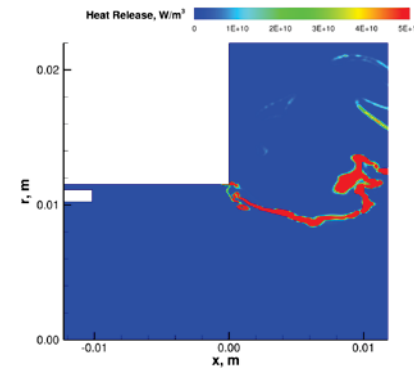


2D Shows Attached Flame

No
swirl



Swirl





Three-dimensional Study

Examine the effect of swirl when exposed to the larger amplitude consistent with the experimental results

Remove the axisymmetric assumption

Swirl is imposed using a boundary condition, not geometry

$$u_{\theta}(r) = u \cdot \left(\frac{r}{R_s} \right) \sin(\theta_S)$$

Four cases:

Baseline

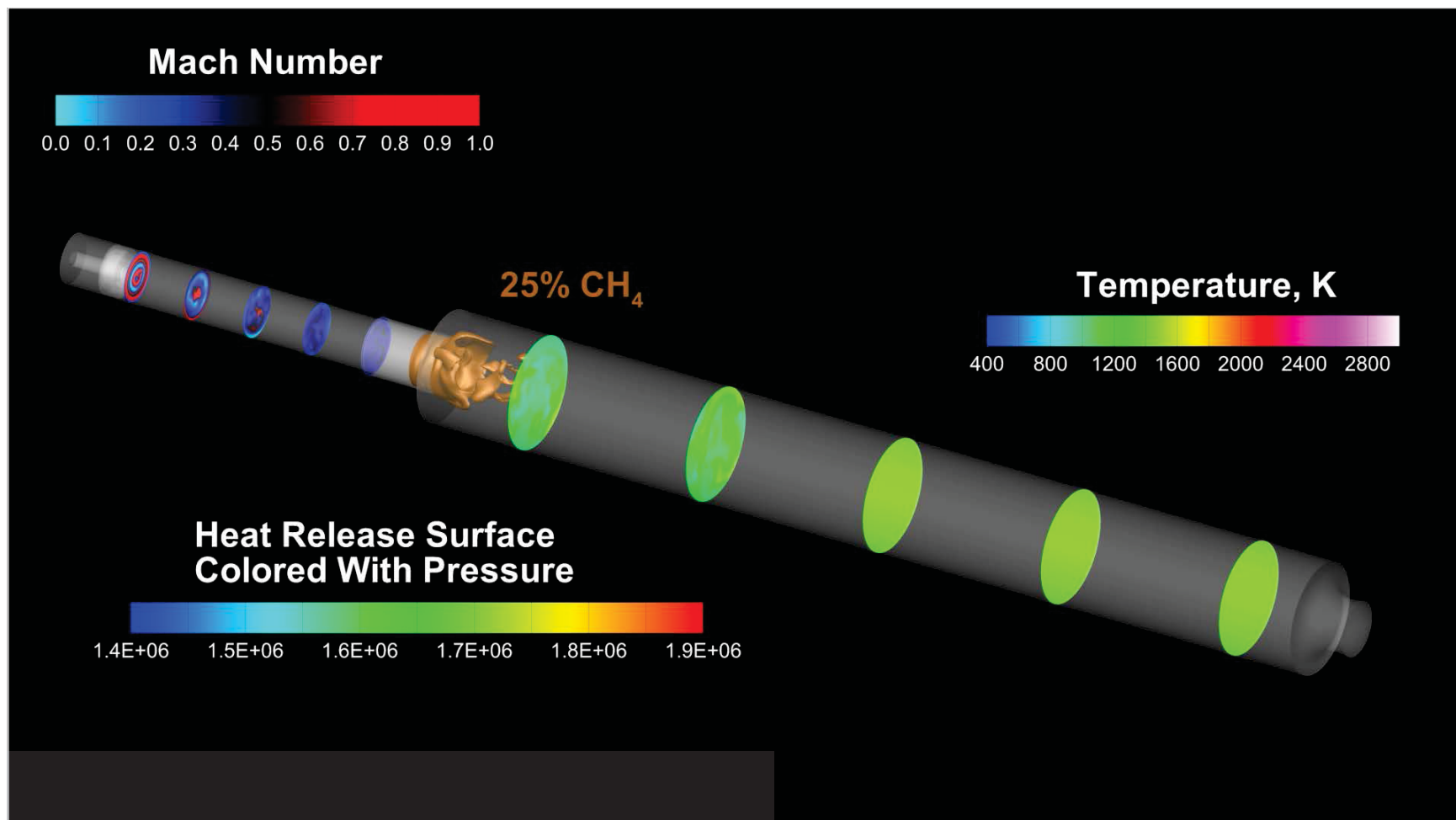
3° Swirl

9° Swirl

15° Swirl

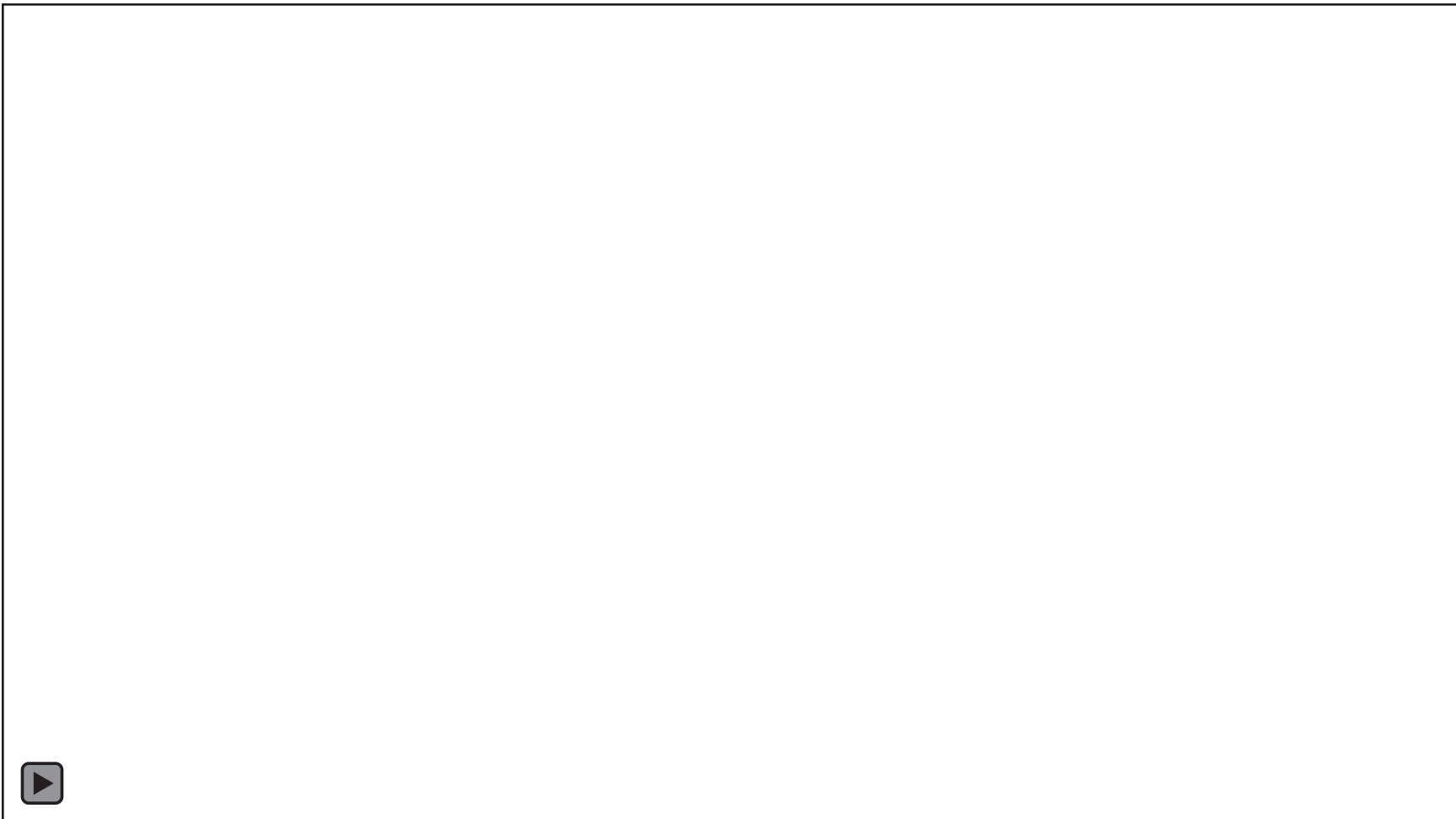


Simulation without Swirl





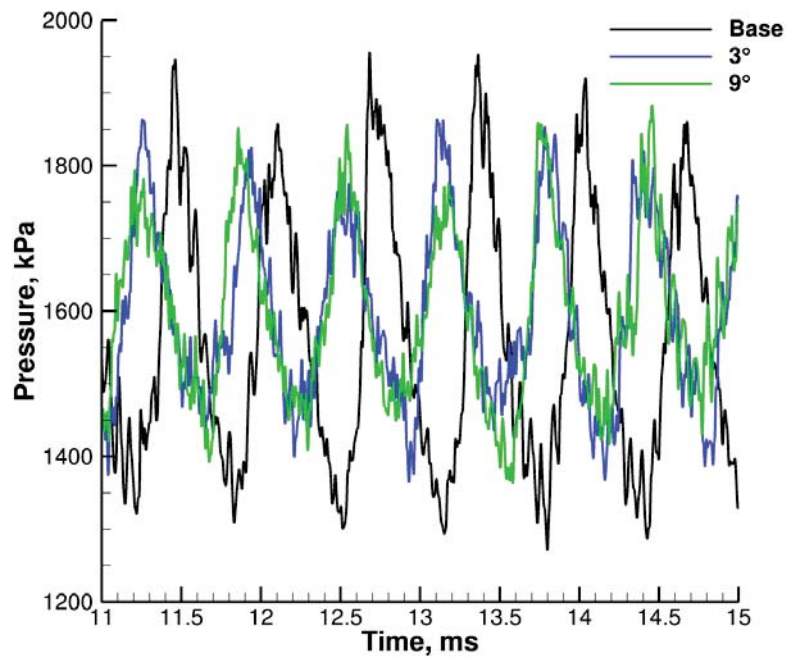
Simulation with Swirl



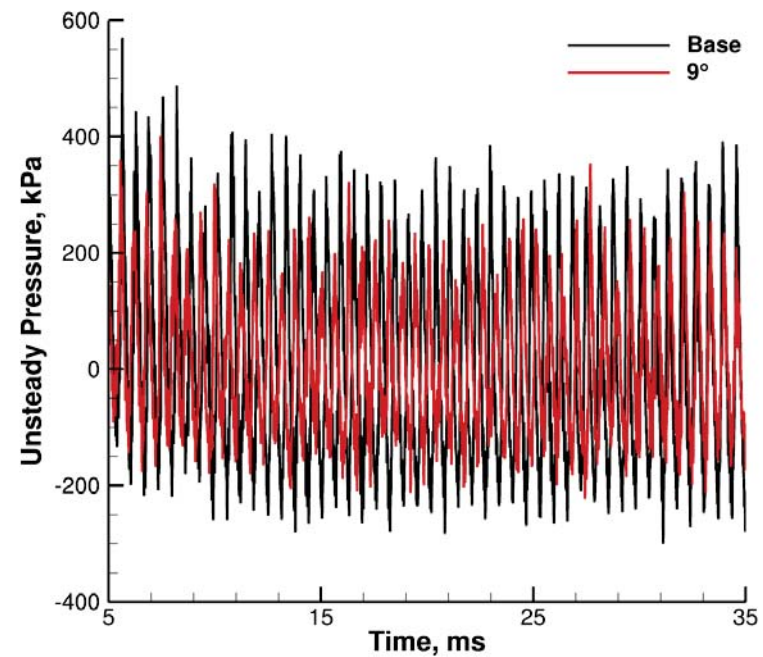


Pressure Amplitude

Swirl has a wider trough with more unsteady fluctuations

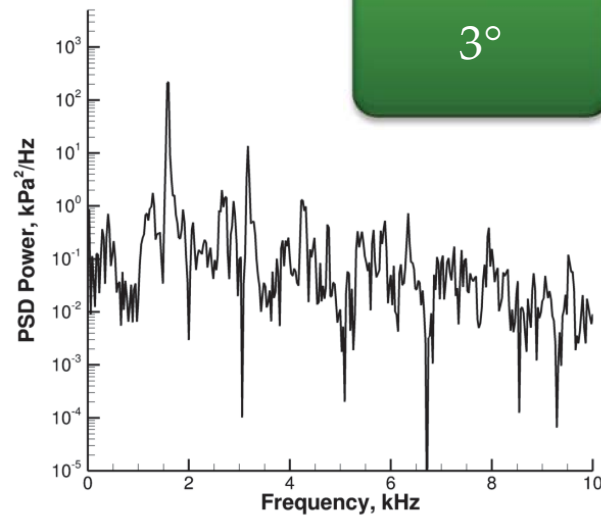
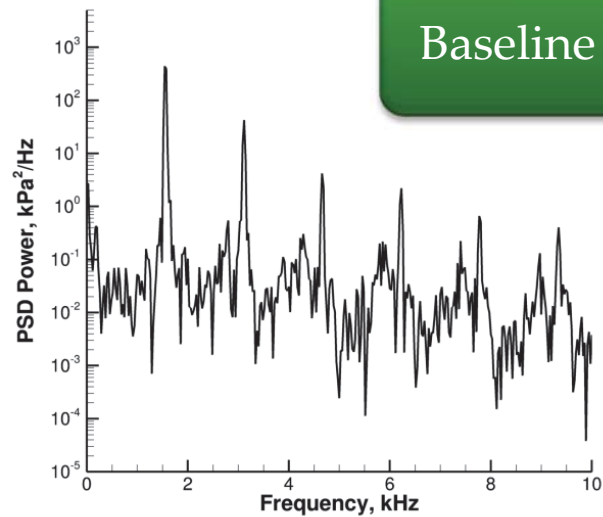


Swirl has a lower amplitude.



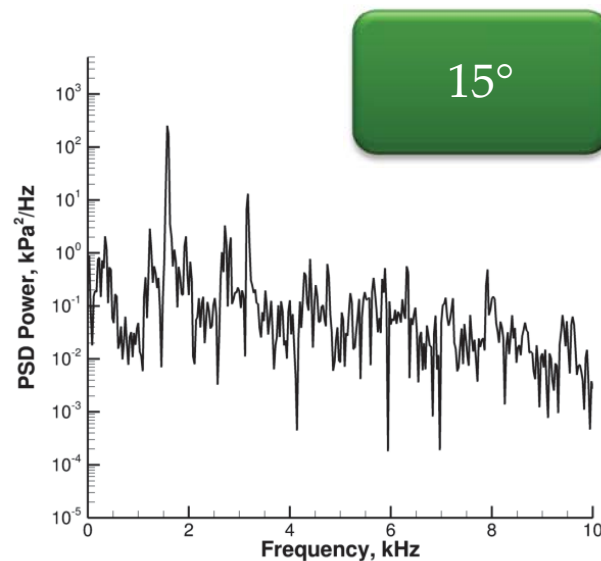
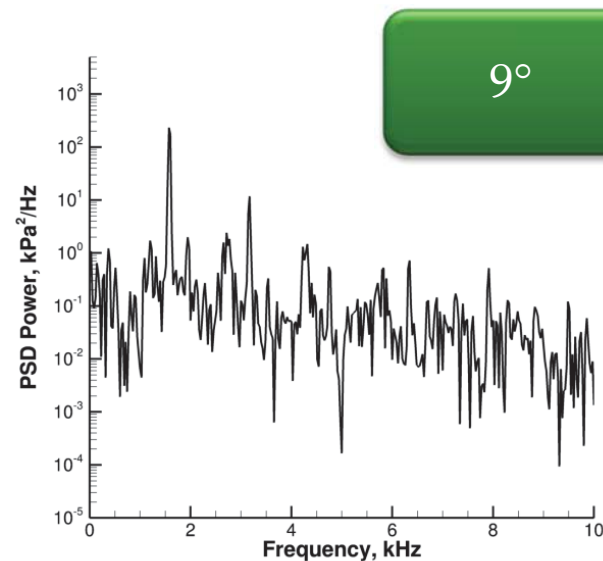


Power Spectral Density Analysis



Swirl has lower amplitudes

Higher order modes are more difficult to identify with swirl



Unknown mode between L1 and L2 for each swirl case



Amplitudes

PSD data is integrated using the FWHM method to determine the peak-to-peak pressure for each mode.

Mode	Baseline		3°		9°		15°	
	f , Hz	p' , kPa	f , Hz	p' , kPa	f , Hz	p' , kPa	f , Hz	p' , kPa
1	1543	349.10	1600	265.88	1571	248.80	1571	251.77
Unknown	—	—	2886	17.37	2714	29.72	2714	21.55
2	3114	87.55	3171	61.19	3171	60.66	3171	66.19
3	4629	36.25	4723	28.47	4723	25.59	4723	27.65

9° of swirl had the greatest reduction, about 30%

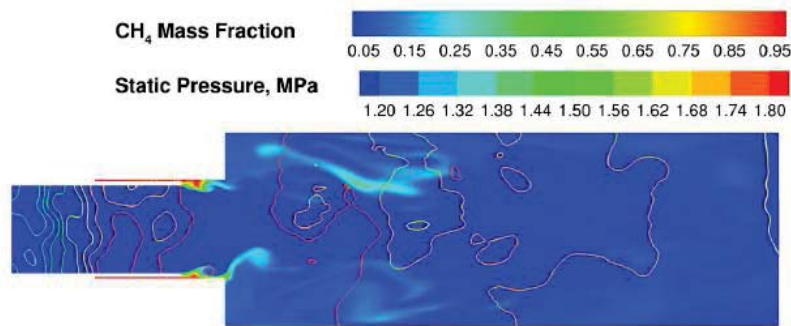
Amplitude reduction is less than the 2D prediction

The unknown mode has a weak amplitude.

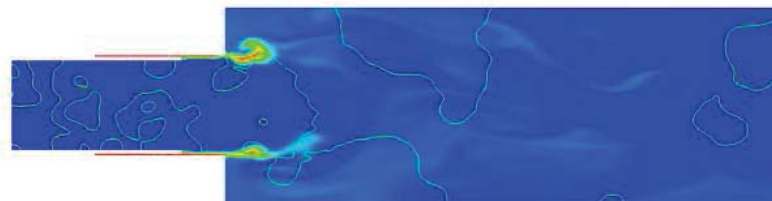
Baseline compares well with experimental results



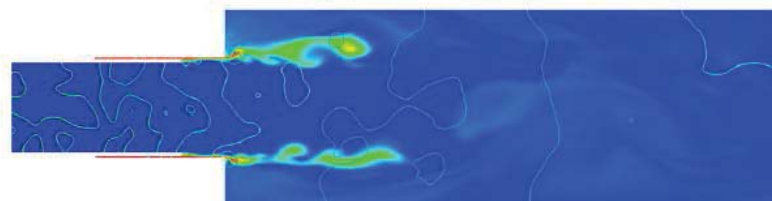
Methane Cycle



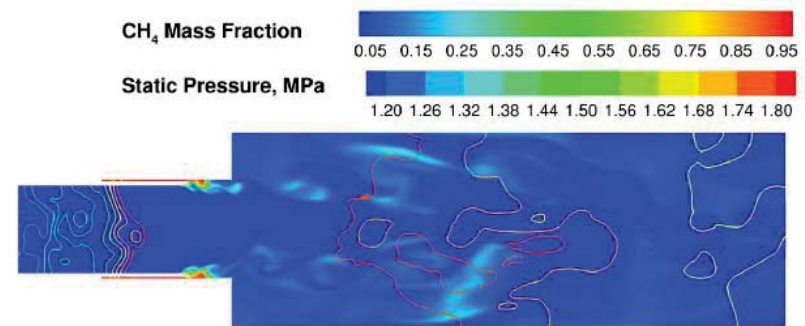
(a) Time 1.



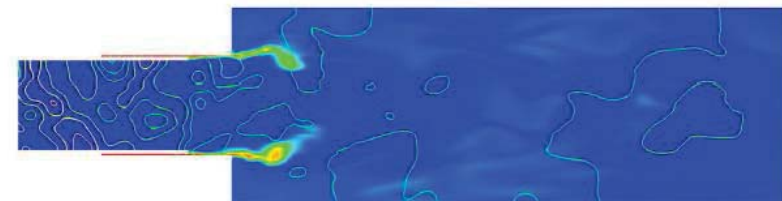
(c) Time 2.



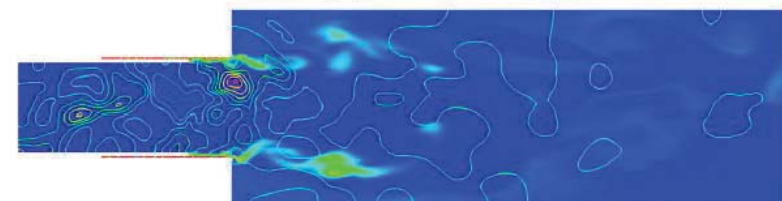
(e) Time 3.



(b) Time 1.



(d) Time 2.



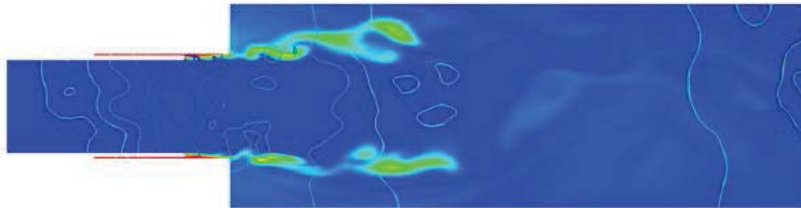
(f) Time 3.

No Swirl

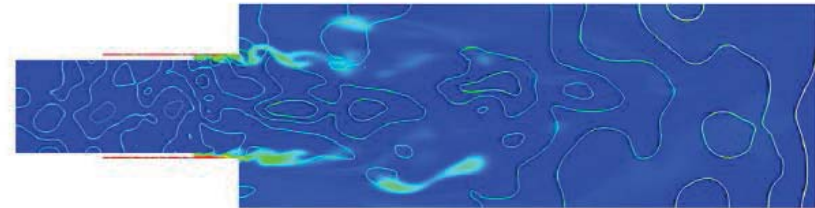
9° Swirl



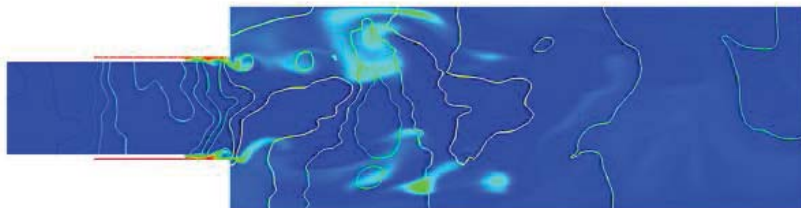
Methane Cycle II



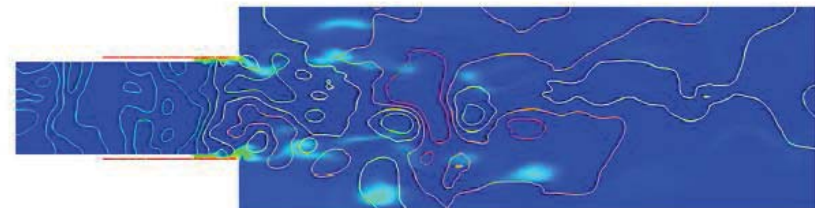
(g) Time 4.



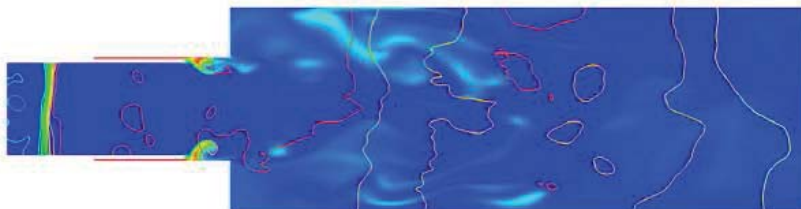
(h) Time 4.



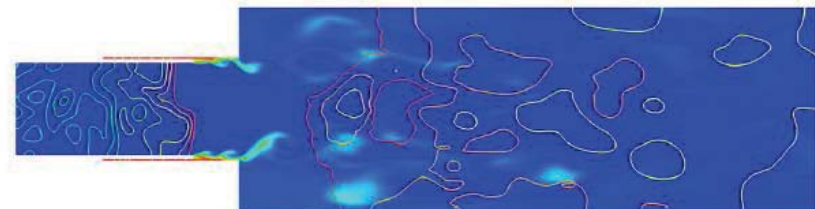
(i) Time 5.



(j) Time 5.



(k) Time 6.



(l) Time 6.

No Swirl

9° Swirl



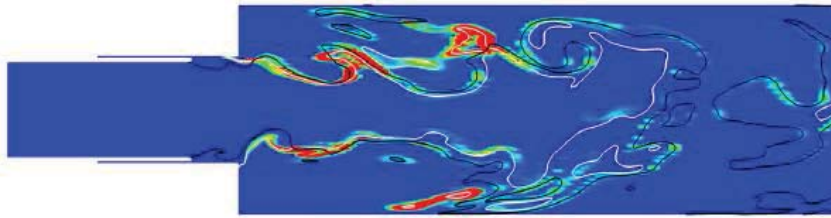
Heat Release Cycle



Heat Release, MW/m³




0 15000 30000 45000 60000 75000 90000

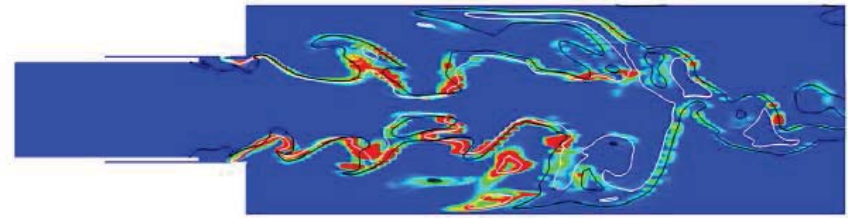


(a) Time 1.

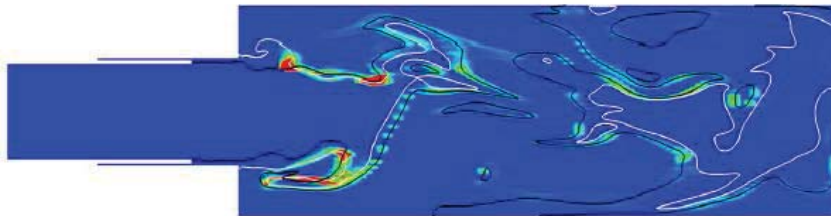
Heat Release, MW/m³



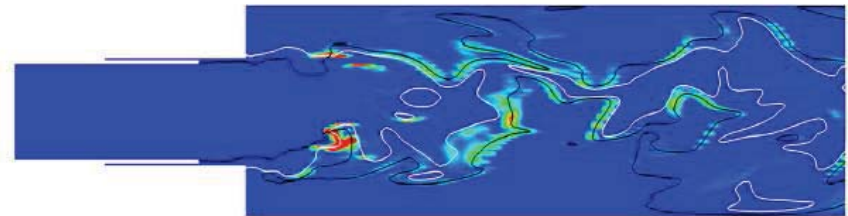
0 15000 30000 45000 60000 75000 90000



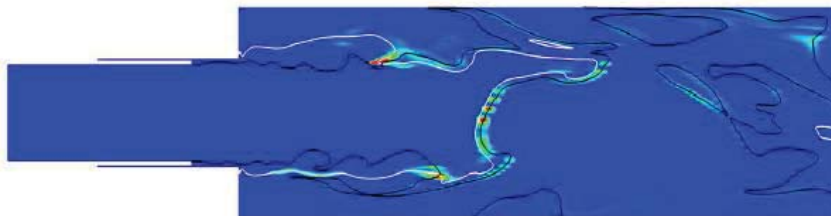
(b) Time 1.



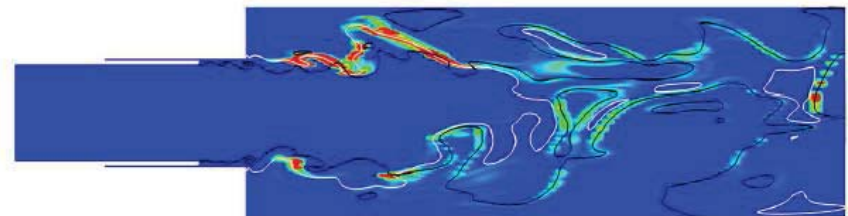
(c) Time 2.



(d) Time 2.



(e) Time 3.



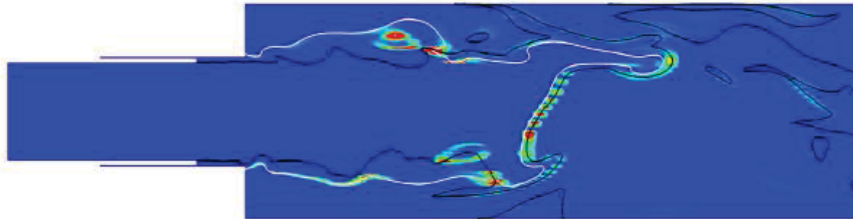
(f) Time 3.

No Swirl

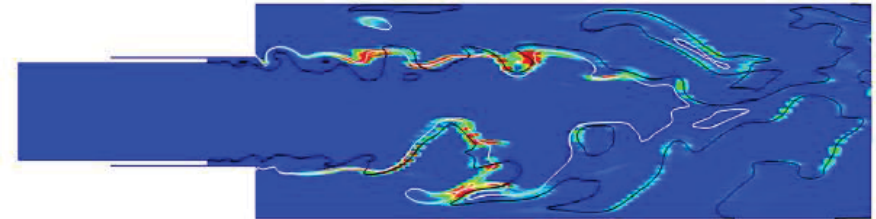
9° Swirl



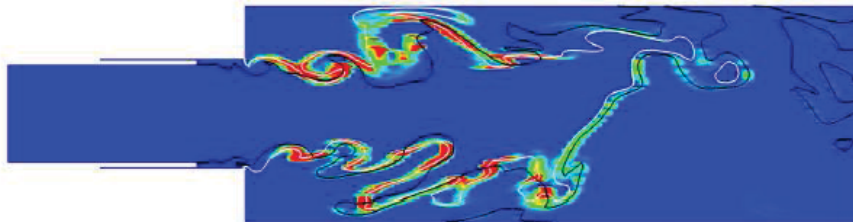
Heat Release Cycle II



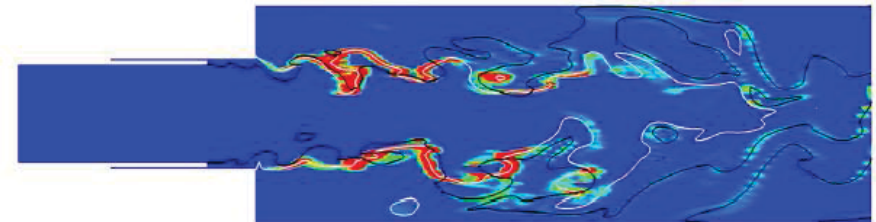
(g) Time 4.



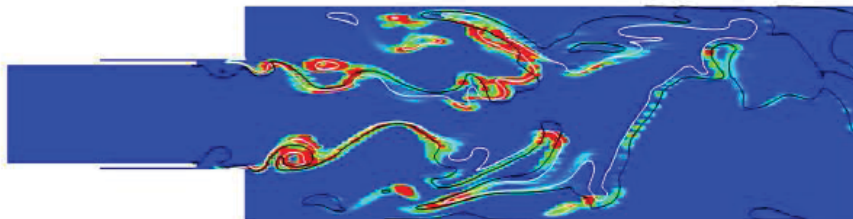
(h) Time 4.



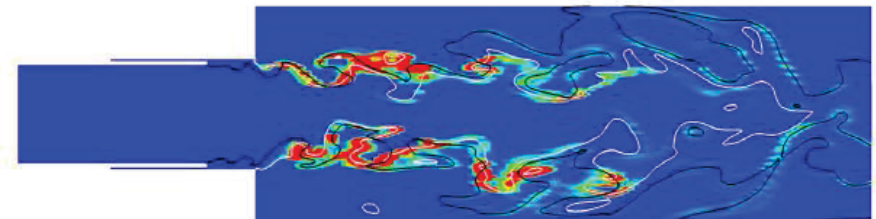
(i) Time 5.



(j) Time 5.



(k) Time 6.



(l) Time 6.

No Swirl

9° Swirl

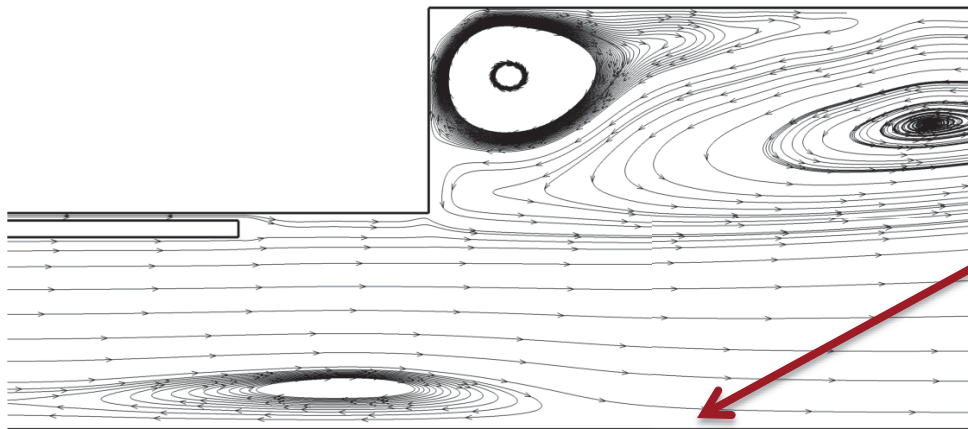


Lack of a CTRZ

Central toroidal recirculation zones can be found in flows with swirl.

The CTRZ has a stabilizing effect

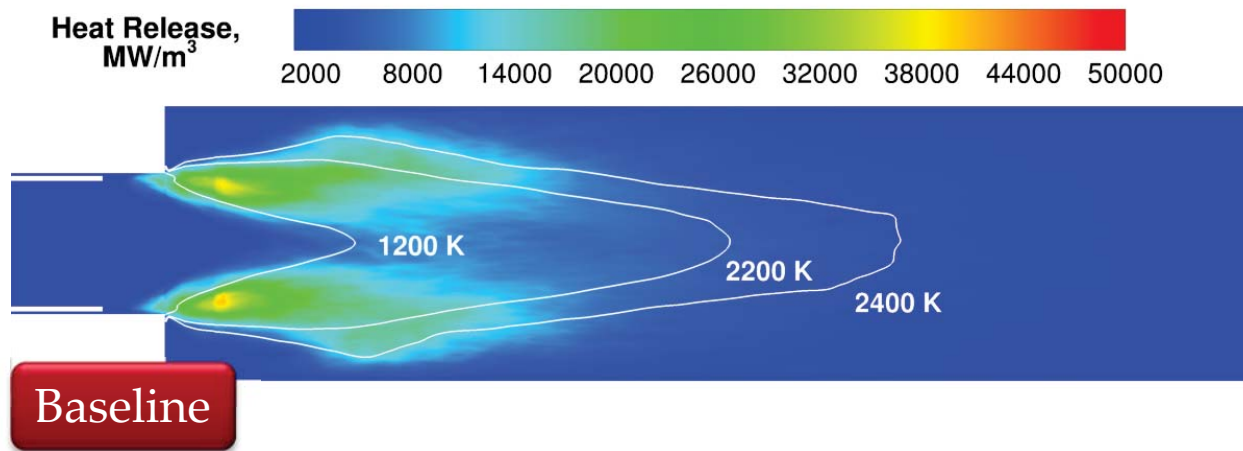
A CTRZ was found in 2D but not 3D



Possibly a result of
the artificial
centerline boundary
condition

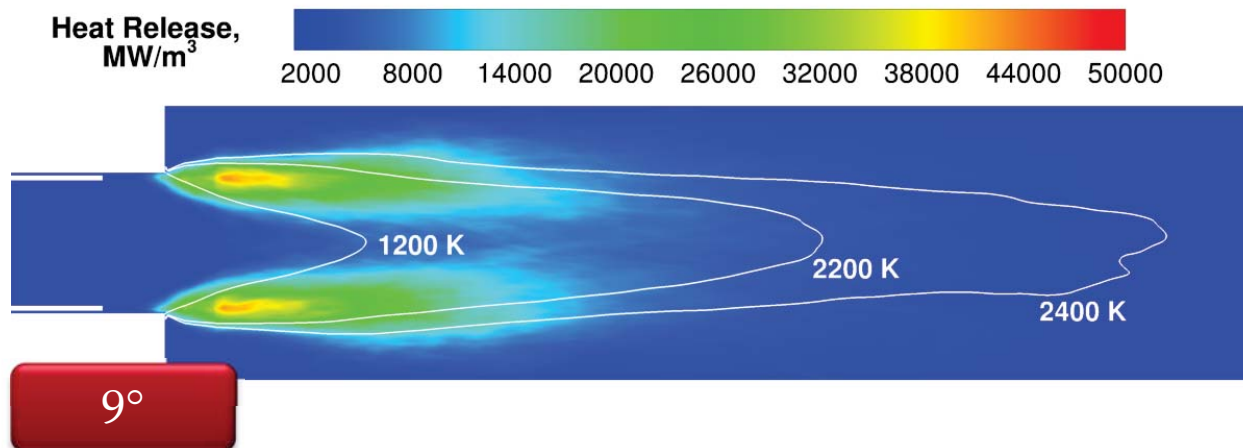


Time Averaged Flowfield



Heat release is similar for all three swirl cases

Swirl shows that the heat release that is confined to the shear layer



No “bump” in heat release

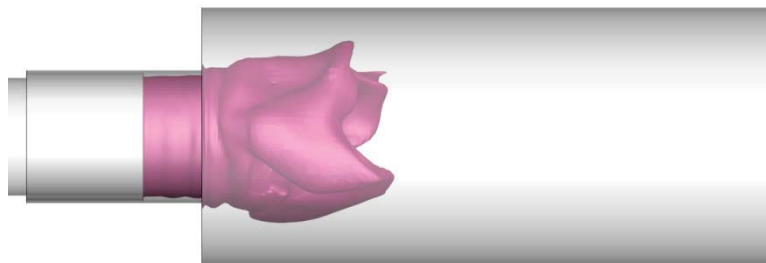
No evidence of a CTRZ in 3D!



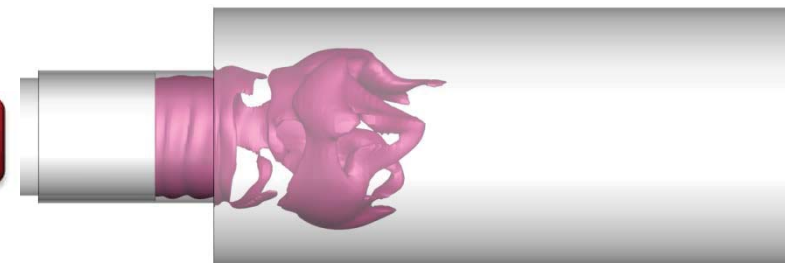
Accumulation of Fuel

Cycle analysis showed that heat release resumes quickly in the swirl case compared to the baseline

There is less fuel accumulation in the cycle and evidence of consumption sooner



50%



75%



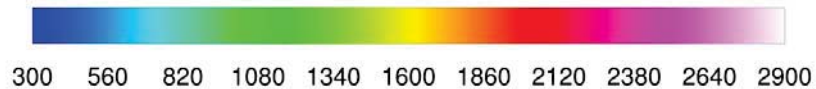
Baseline

9°

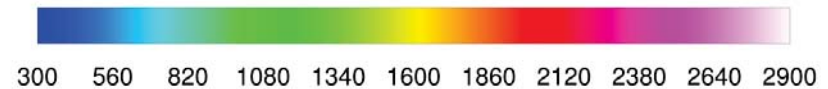


Injection Differences

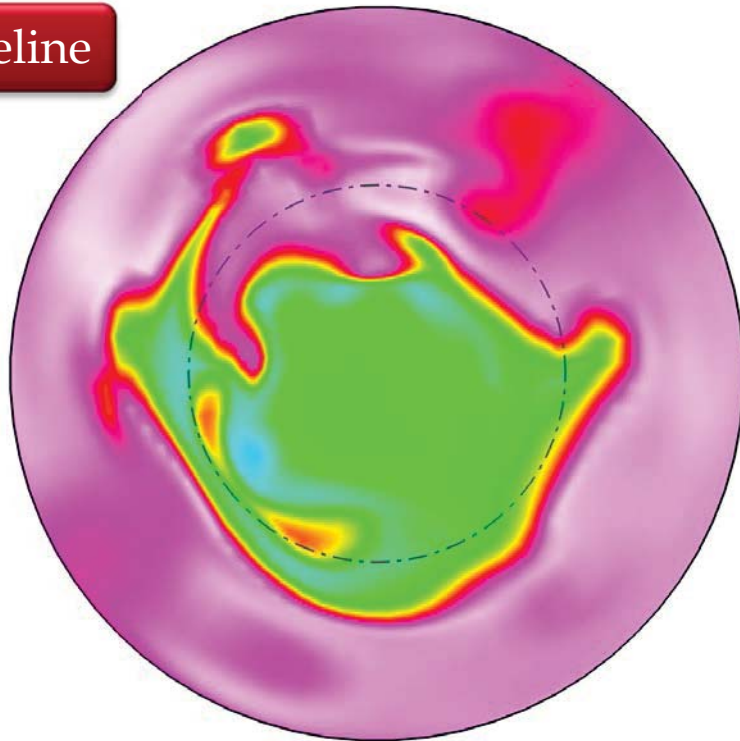
Temperature, K



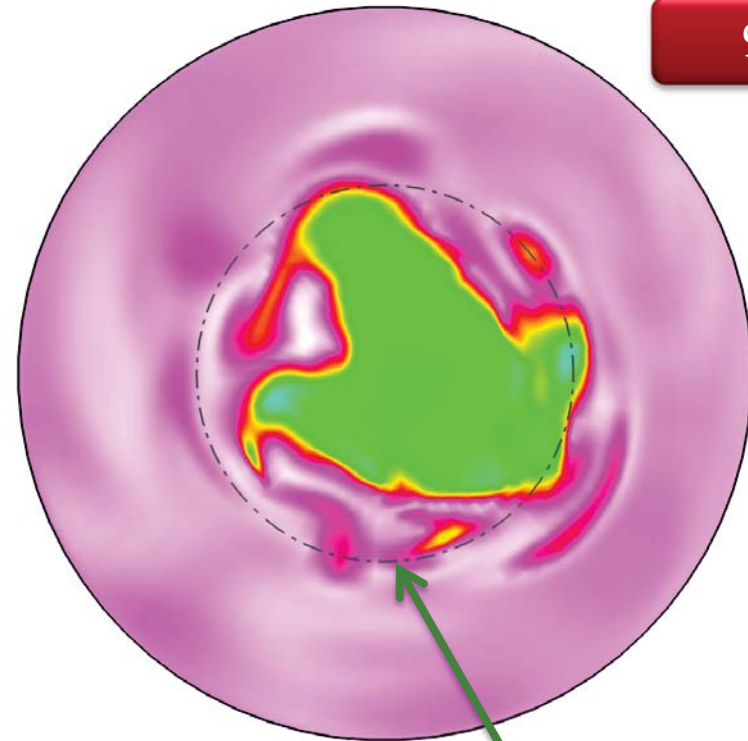
Temperature, K



Baseline



9°



Ox post diameter

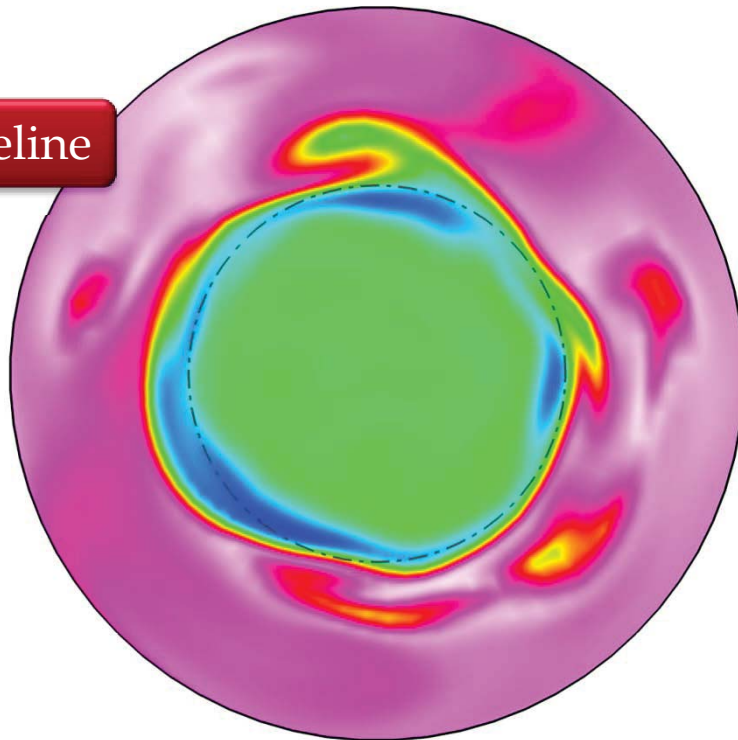
20%



Injection Differences

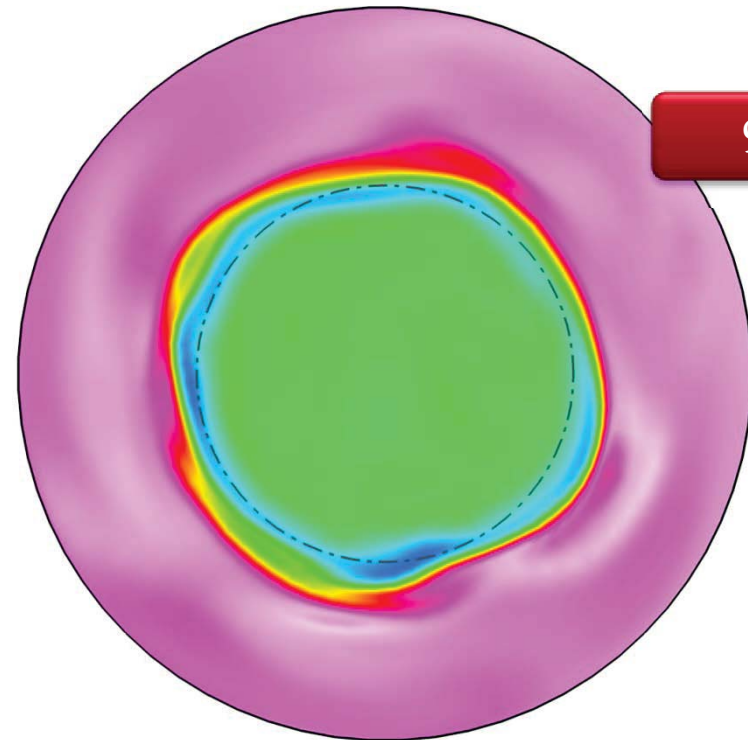


Baseline



More radial
expanse

9°



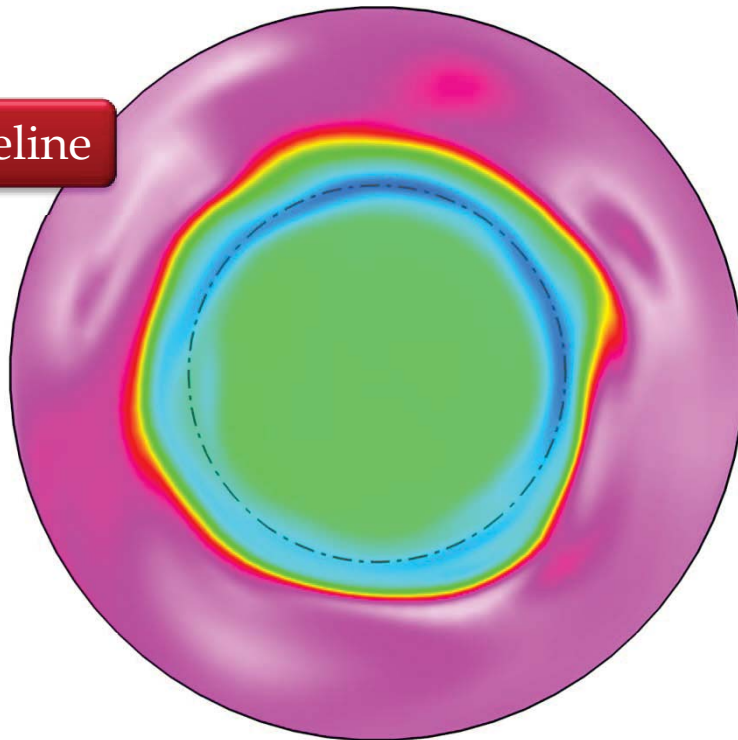
Less pure fuel
regions

40%



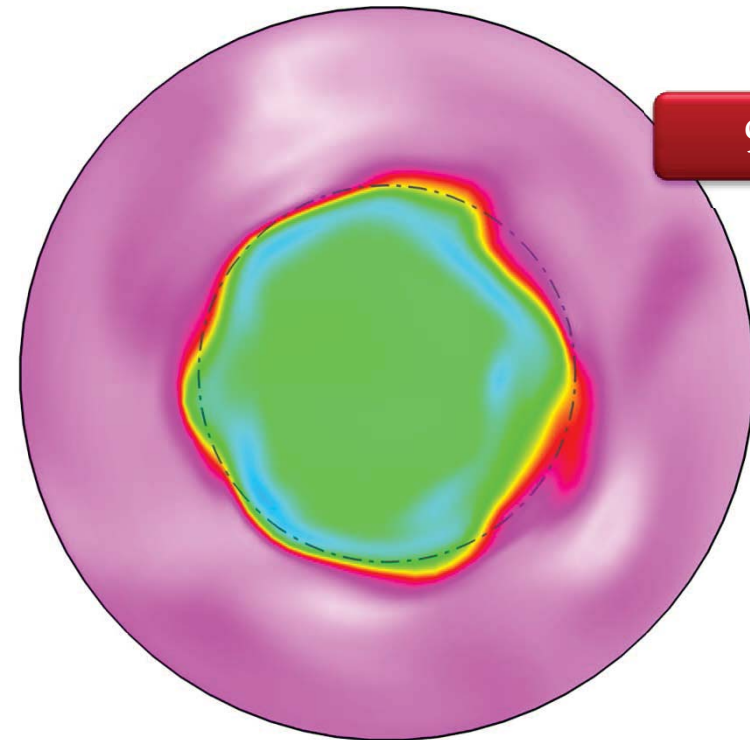
Injection Differences

Baseline



More radial
expanse

9°



Less evidence of
fuel

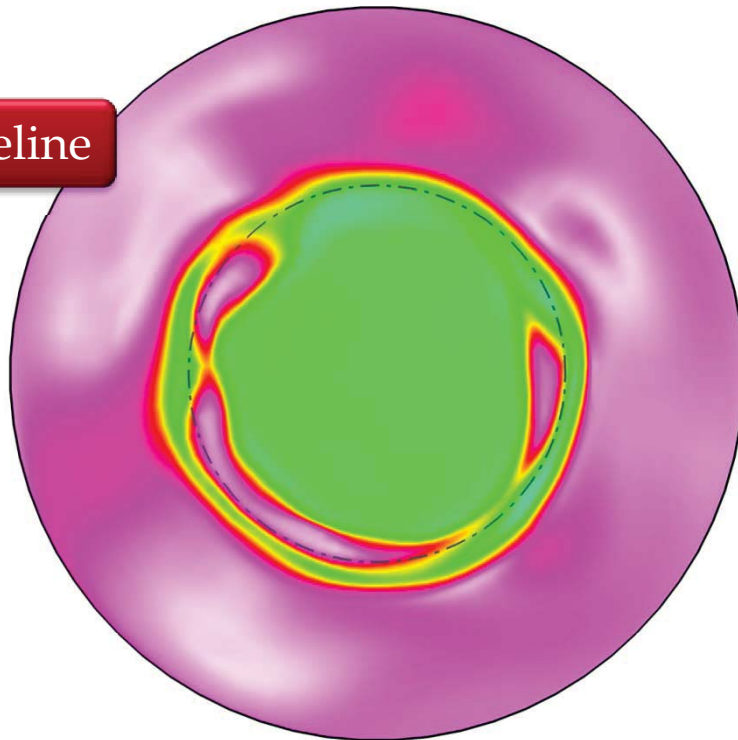
70%



Injection Differences

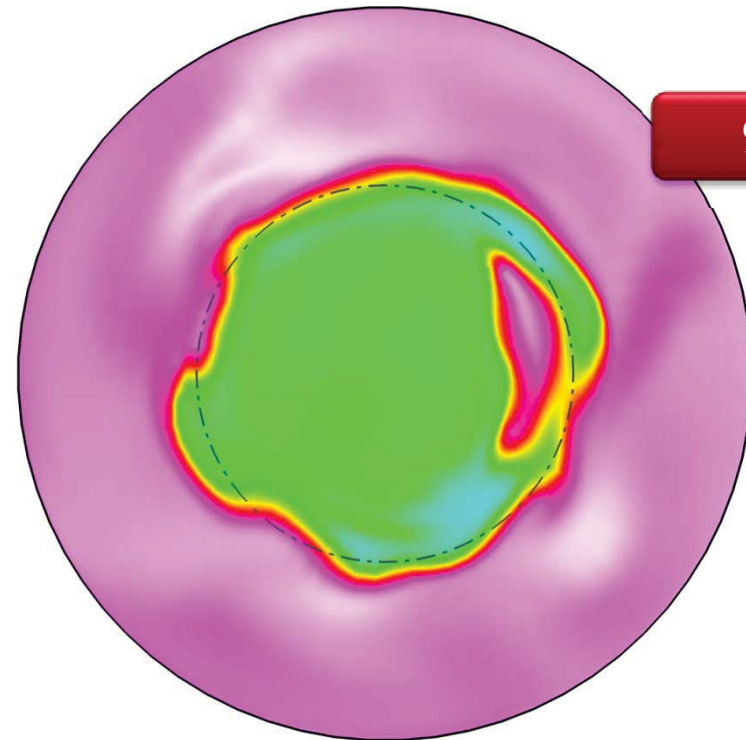


Baseline



More radial
expanse

9°



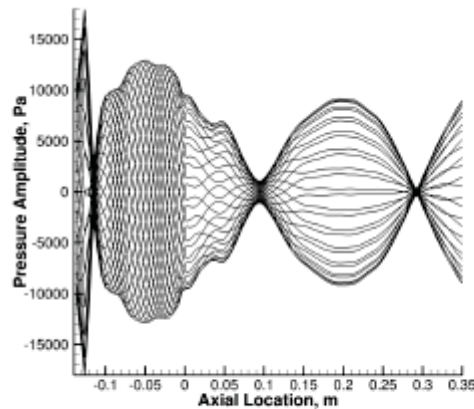
Less evidence of
fuel

80%

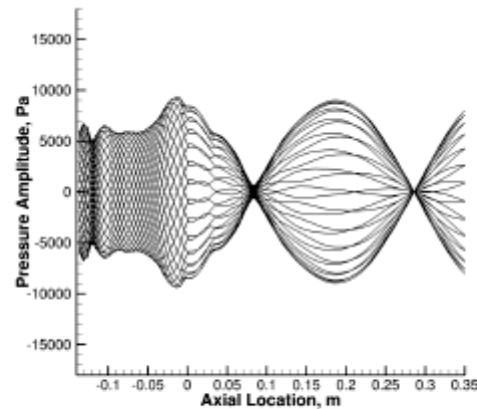


Unknown Mode

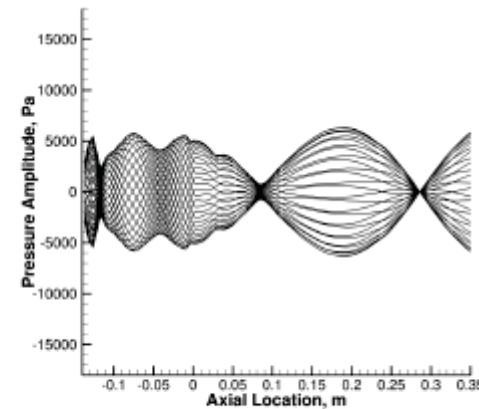
Unknown mode was found in the swirl cases with a frequency between the first and second longitudinal modes



(a) 3° swirl, pressure.



(b) 9° swirl, pressure.



(c) 15° swirl, pressure.

No evidence of a PVC mode or spinning mode

A similar mode was found in a 3.5" simulation which had a similar amplitude to the swirl cases.



Summary

A numerical investigation of the effect of swirl on an unstable single-element gas-gas rocket engine was undertaken

The addition of swirl to the fuel reduced the amplitude by 30%

The reduction of amplitude was a result of:

Improved mixing
between the fuel
and oxidizer

Shorter recovery
time of the fuel
cut off event

More continuous
heat release
throughout the
cycle

The percent amplitude reduction in 3D was not as great as 2D, but had a similar absolute reduction in amplitude

2D simulations should be used to reduce the number 3D simulations



Effect of Swirl on an Unstable Single-Element Gas-Gas Rocket Engine



Matthew E. Harvazinski,
Venkateswaran Sankaran,
and Douglas G. Talley

DISTRIBUTION STATEMENT A: Approved for public release; distribution is unlimited.